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Procedia Engineering 10 (2011) 1035–1040

Engineering Procedia

ICM 11

Indentation based life assessment for boiler tubes of fossil power plants

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Abstract

Boiler tubes of fossil power plant are used in high temperature and high pressure operating conditions are required to resist creep damage, fatigue cracking, and corrosion damages. Especially, X20CrMoV12.1 (12%Cr) steel has been widely used for superheater and reheater tubes of power plants due to its improved creep strength and higher oxidation resistance. Long-term service at the elevated temperature causes deterioration of mechanical property of materials as a result of changes in microstructure. Thus the accurate knowledge of degradation or life consumption level considering strength decrease is necessary to make a plan for the effective operation and maintenance.
In this paper, some material properties such as yield strength, tensile strength, of X20CrMoV12.1 steel tubes were experimentally evaluated by portable indentation tester. Also damage evolution parameters of continuum damage models are modified to determine remaining life of boiler tubes. Which methodology was developed for the in-situ experiment for plant facilities.

Selection and peer-review under responsibility of ICM11
Keywords : indentation, life, boiler tube, power plant

1. Introduction

Boiler superheater and reheater tubes are operated at high pressure and high temperature condition. So, the tube materials are required enough strength to resist creep, corrosion and oxidation. Several super critical boilers of which pressure is 22MPa, temperature 540℃ has been built on fifteen years ago in Korea. It is well known that X20CrMoV12.1 tube steel has been in service for the superheater, reheater tubes, main steam pipes, boilers, turbine cases in thermal, power generation plants since the early 1960s.

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Selection and peer-review under responsibility of ICM11
doi:10.1016/j.proeng.2011.04.171

Nomenclature

D	Damage		
D_{el}	Elastic damage [%]	α	Coefficient of elastic damage
D_{pl}	Elastic damage [%]	β	Coefficient of elastic damage
E_{aged}	Elastic modulus of aged tube [GPa]	E_{virgin}	Elastic modulus of virgin tube [GPa]
Hv_{aged}	Hardness of aged tube	Hv_{virgin}	Hardness of virgin tube

X20CrMoV12.1 steel is developed based on the corrosion-resistant 13% Cr high temperature steels containing up to 0.25% C in tempered condition[1]. In case of plant maintenance strategy, life assessment or reliability evaluation is necessary to determine replacement time and scope for failure susceptible facilities such as boiler. Thus, it is necessary to develop advanced technology to improve accuracy of life assessment result for more reliable study. Even though there are usual accelerated degradation tests such as tensile test, creep test, and etc., these methods are time consuming and expensive, unsuitable for size limited components. Computer aided analytic methods have general uncertainty by many assumptions such as operating condition, geometric uncertainty, material uncertainty. Many kind of non-destructive techniques, such as replica analysis, electronic resistance test and ultrasonic test, have been developed for lifetime prediction, but they also have many limitations[2]. With these difficulties in life assessment, several non-destructive methods have been used to evaluate microstructural degradation in order to predict mechanical property change and calculating remaining life[3]. Hardness tests are generally used to determine degradation level, up to now, since it is relatively easy. However a larger scatter was observed for the same specimens and the hardness is a kind of indirect measurement values. Also repeatability and reproducibility causes to high uncertainty of life assessment result. An indentation test is a kind of non-destructive techniques and is useful to determine material properties in specific components. This method can measure various mechanical properties such as elastic modulus, tensile strength, and residual stress by analyzing the indentation load-depth curve (Oliver & Pharr, 1992; Lee, & Kwon, 2006). Oliver and Pharr methodology uses the unloading stiffness to calculate the material compliance and the amount of sink-in, which is required to find the exact contact area[3]. Lemaitre and Dufailly originally measured the modulus using strain gauges from unloading curves. Mechanical properties of high alloy ferrite steel for boiler tubes are degraded in long-term service under high temperature and high pressure operation condition. According to the microstructure and stress-strain curve of the virgin and degraded material, with increase of aging time, strength decreased and ductility increased[4] .

In this paper, for the remaining life assessment, damage evolution parameters of continuum damage models are proposed and experimentally evaluated by analyzing of mechanical properties using portable indentation tester. Furthermore, the effects of aging on the mechanical properties of virgin and used specimen were investigated by microstructure analysis.

2. Damage parameters

The direct methods evaluate damage consumption through density, surface area fraction or volume fraction measurements. However, the direct measurement of damage as the surface density of micro defects is not easy and is used only in limited laboratories. Those methods are questionable related with the required high levels of accuracy for quantitative analysis of ductile damage. Also the direct measurement of damage is used in limited laboratory conditions well equipped for micrography. Thus Lemaitre and Dufailly proposed the inverse method to evaluate the damage by the coupling between damage and elasticity (or plasticity).

2.1 Original model[5]

In the case of isotropic elasticity change, elastic modulus based damage quantification is based on the stiffness change due to the evolution of damage, and is expressed as below;

$$D_E = 1 - E_{aged} / E_{virgin} \tag{1}$$

where E_{aged} is the Young's modulus of undamaged elasticity and E_{virgin} is the actual modulus of damaged elasticity. Hardness, meanwhile, is influenced by the softening effect of damage. Hardness based damage quantification is defined as

$$D_H = 1 - \frac{H_{aged}}{H_{virgin}} \frac{\sigma_y}{\sigma_u} \tag{2}$$

Where H_{virgin} is the hardness of undamaged position and H_{aged} is the actual hardness of damaged position. Billiardon and Dufaily proposed that this equation allows for the measurement of surface damage fields with in situ measurements.

2.2 Modified damage parameter

Elastic modulus based damage quantification is based on the uniaxial law of elasticity and the change of elastic modulus is relatively small in the actual field. Otherwise hardness based damage quantification follow experimental result that actual yield stress is related to the hardness. The damage parameter here is modified to consider the coupling between elasticity and plasticity damage.

$$\begin{aligned} D_{\mathrm{mod}} &= f(D_E, D_H) \\ &= \alpha f_1(E_{aged}, E_{virgin}) + \beta f_2(H_{aged}, H_{virgin}, \sigma_y, \sigma_u) \end{aligned} \tag{3}$$

For this model, damage parameters including tensile properties were obtained by portable indentation tester and hardness tester. α and β are constant and those have different values according to the materials. Detail explanations about damage evaluation algorithm are described in reference [6].

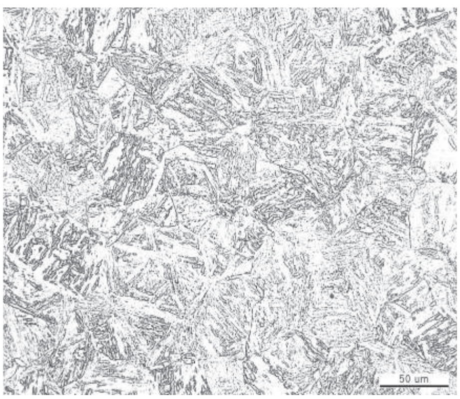
3. Experiments procedure

The specimens used here were X20CrMoV12.1 (DIN 17175) steel called X20, widely used for super heater tube in power plant boiler. Two types of specimen were prepared from used tube and unused tube samples. Tubes, collected from final super heater inlet, were cut into cylindrical specimens with diameter of 38mm and thickness of 5 mm. Indentation test and hardness tests were carried out with a portable indentation system and hardness tester. At least 8 sets of test data according to the angle are were obtained from indentation and hardness tests for each material, and each average values were used for calculating damage consumption rate. After measuring elastic modulus, yield stress, tensile stress and hardness for each tube, damage consumption rate can be calculated from modified damage parameter in equation (3). If operating hour or the number of cycles of target plant, installed by used tubes, finally, remaining life of tubes is determined by the time or number of cycle selected.

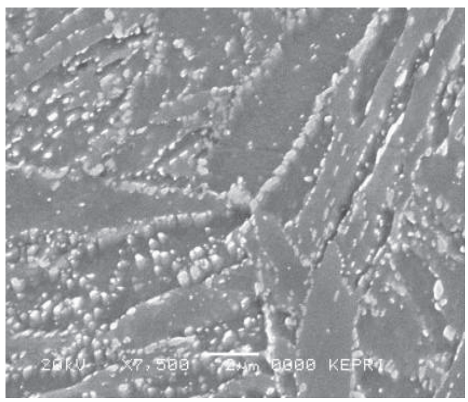
4. Result and discussion

4.1 Microstructure

It is well known that, X20CrMoV12.1 alloy steel pipe, the carbides in the exposed pipe coarsened heavily with enriching alloying elements of Cr and Mo from the matrix during long-term service exposure, so the coarsened carbides reduce both precipitation and solid solution strengthening mechanisms and the degradation of the material is mainly related to carbide coarsening[7-8]. Fig. 4 shows the microstructure of X20 tubes used for 64,072 hour at 569 ℃. The microstructure from OEM and SEM is observed to be tempered martensite, which are constituent dispersions of Fe_3C in α -ferrite sites. And lath-shaped grains appear in alternate light and dark layers. However, there is no significant change in microstructure in comparison with unused same material and it shows that microstructure have no relation with the mechanical property variation. As a result, it is difficult to know degree of material degradation by microstructure analysis. This means that life consumption by material degradation can be estimated through considering material properties including the hardness, yield stress and tensile strength instead of OEM or SEM observations.



(a) OEM image



(b) SEM image

Fig. 1 Microstructure of aged X20CrMo12.1V

4.2 Mechanical properties

The elastic modulus is obtained from indentation load-depth curve according to the Oliver and Pharr's approach and the yield strength is measured from the intersection point of the flow curve and a line with a slope of the elastic modulus 0.2% offset from the origin. In case of the ultimate tensile strain, it is determined by Dieter's instability theory in tension. If measured materials do not follow power laws hardening model, there is limitation to use those algorithm. Table 2 shows mechanical properties and constant values of virgin and used tube. Averaged values of obtained data are used to calculate damage parameters. It is seen that the strength (Elastic modulus, YS, and TS) of virgin tube is higher compared to other used tube. Also it is observed that there are significant differences in those properties.

Table 2 Mechanical properties and constant values

	Elastic modulus (GPa)	Hardness (Hv)	Yield Stress (MPa)	Tensile Stress (MPa)	n	K
Virgin tube	205.47	246.9	492.4	723.4	0.1541	1117.8
	197.46	237.6	490.3	716.2	0.1461	1090.9
	205.26	247.7	529.7	756.0	0.1471	1153.6
	200.49	244.0	536.2	764.7	0.1475	1167.8
	209.48	247.7	539.5	761.9	0.1621	1194.0
	211.35	246.9	533.0	765.7	0.1658	1207.5
	219.78	247.9	525.2	747.9	0.1487	1144.6
	205.59	248.0	525.7	737.1	0.1412	1112.6
Used tube	190.90	237.6	434.4	751.5	0.1362	1099.3
	195.80	238.0	439.1	736.1	0.1278	1055.2
	186.30	236.0	448.0	742.7	0.1452	1150.8
	187.90	238.5	456.9	732.7	0.1501	1182.5
	196.80	238.5	523.9	738.8	0.1565	1227.7
	194.70	236.7	434.5	730.4	0.1486	1170.1
	198.00	245.0	492.6	731.6	0.1441	1172.0
	186.80	235.8	441.0	733.2	0.1690	1220.1

4.3 Life assessment

The damage parameter D_{mod} is calculated by using measured tensile properties and hardness for tubes. A remaining life is obtained from damage parameter and operation history using equation (4).

$$t_r = \left(\frac{1}{D_{mod}} - 1 \right) \cdot t_{op} \tag{4}$$

where t_r is a remaining life and t_{op} is a operating hour up to now. If the number of cycles to the present is given, remaining life t_r is replaced by remaining cycles N_r. According to the result of assessment based on averaged values, the remaining lifetime of the 64,072 hours tubes is about 100,538 hour. Because design lifetime of boiler tubes is approximately 200,000 hours, remaining life considering operation hour are within reasonable value relatively[9]. However, measurement of the same material property does not yield the same value such as Table 2 and causes to the uncertainty of the remaining life.

Additional probabilistic analysis is carried out in order to verify reasonability of process and assessment result. The capability analysis in Fig. 8 shows that with the LSL=200,000. Potential capability C_{pk} is the simplest and most straightforward indicator of process capability. It is defined as the ratio of the specification range to the process range. This ratio expresses the proportion of the range of the normal curve that falls within the engineering specification limit[10]. Since C_{pk} is greater than 1, there are no (or almost no) results fall outside specification limits. As a result, indentation based life assessment method for X20CrMoV12.1 tube

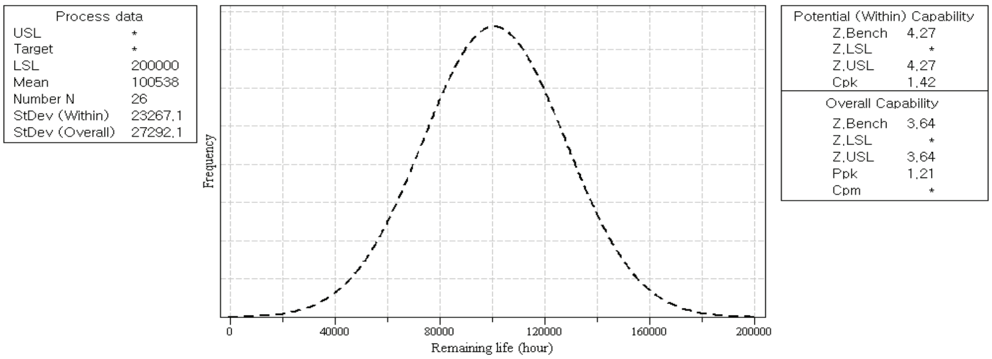


Fig. 2 Process capability analysis for remaining life

5. Conclusion

In this study, indentation based life assessment approach of boiler tubes is proposed. The mechanical properties for modified damage parameter were determined by using portable indentation tester and hardness tester. Even though the microstructures of X20CrMoV12.1 steel were observed by Optical Microscope, noticeable changes are not shown between virgin and used tubes. As an alternative, modified damage parameter, based on hardness and elastic modulus based damage quantification, was introduced to determine remaining life of X20CrMoV12.1 boiler tube. The remaining lifetime of the 64,072 hours tubes is about 100,538 hour. Because design lifetime of boiler tubes is approximately 200,000 hours, remaining life considering operation hour are within reasonable value relatively. The measurement of strength variation using portable indentation and modified damage parameter shows good potential for life assessment of plant components. Furthermore, in-situ monitoring of material properties and quick life assessment for on-site facilities will be possible using this method.

Acknowledgements

This research was supported by a KETEP, which are supported by Ministry of Knowledge and Economics, Korea

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